Using evolving physical models for musical creation in the GENESIS environment

Olivier Tache, Claude Cadoz

USING EVOLVING PHYSICAL MODELS FOR MUSICAL CREATION IN THE GENESIS ENVIRONMENT

TACHE Olivier
ICA Laboratory
INPG, 46, avenue Félix Viallet
38031 Grenoble, France
Olivier.Tache@imag.fr

CADOZ Claude
ACROE & ICA Laboratory
INPG, 46, avenue Félix Viallet
38031 Grenoble, France
Claude.Cadoz@imag.fr

ABSTRACT

Physical modelling schemes are well known for their ability to generate plausible sounds, i.e. sounds that are perceived as being produced by physical objects. As a result, a large part of physical modelling research is devoted to the realistic synthesis of real-world sounds and has a strong link with instrumental acoustics. However, we have shown that physical modelling not only addresses sound synthesis, but also musical composition. In particular, mass-interaction physical modelling has been presented as enabling the musician to work both on sound production (i.e. microstructure) and events organization (i.e. macrostructure). This article presents a method for building mass-interaction models whose physical structure evolves during the simulation. Structural evolution is implemented in a physically consistent manner, by using nonlinear interactions that set temporary viscoelastic links between independent models. This yields new possibilities for music creation, particularly for the generation of complex sound sequences that exhibit an intimate articulation between the micro- and the macrostructure.

1. INTRODUCTION

Physical Modelling (PM) schemes have been used by a number of composers [8]. A large majority of these works consider PM schemes as sound synthesis techniques able to produce interesting and plausible sounds, while the macro-structure of the pieces is either written, or generated by other means. In this case, the composer has to switch between several languages or environments during his or her work.

GENESIS [6], which is based on mass-interaction PM, is a music creation environment that unifies the work on micro- and macrostructure, since both are addressed with the same concepts and the same language, those of the CORDIS-ANIMA system [3]. As was demonstrated by Cadoz [4], it is possible to generate an entire piece of music with a single GENESIS model, without any post-processing. Several reasons for composing with PM have been exposed [7]. It should be emphasized that this method has the ability to produce sound sequences that present “natural” qualities, in terms of timing, expressiveness and subtlety of rhythm and timbre changes. As plausible sounds are more relevant to our hearing system than artificial sounds, physically-generated sound sequences may be more relevant to our perception than those generated by more abstract algorithms.

GENESIS, whose building blocks are elementary but still physically meaningful modules, is a highly modular environment. Consequently, the number of potential models is very large. We are currently exploring this “potentiality space” in order to identify and document the most universally useful categories of models, investigating both sound and event generation. We have already discovered a number of event generation schemes, of which some have been presented [4]. This article presents more intriguing models characterized by the fact that their physical structure evolves while they are simulated. These models exemplify a very particular approach to composition with PM, which could be termed *composing the matter*, since it involves creating virtual instruments that exhibit macro-temporal behaviours. We will describe the implementation of structural evolution with nonlinear interactions and then introduce two models that demonstrate some of its possible applications.

2. CONTEXT OF THE STUDY

2.1. The GENESIS environment

2.1.1. *Mass-interaction physical modelling*

GENESIS [6] is a graphical environment for musical creation with mass-interaction PM. It is based on the CORDIS-ANIMA system developed at ACROE and ICA laboratory. In CORDIS-ANIMA, virtual objects are composed of two types of elements, called *modules*:

- Punctual material elements called <MAT> modules. The most used is the MAS module, which represents a mass that behaves according to Newton’s laws.
- Link elements called <LIA> modules. A <LIA> simulates an interaction between two <MAT>. The interactions are of different types: elasticity, friction, nonlinear viscoelasticity, etc.

A <LIA> computes forces according to the position and/or velocity of the two <MAT> modules it links. A <MAT> computes its position according to the forces it receives from the <LIA> modules it is linked with.

Position and force are the two fundamental variables upon which CORDIS-ANIMA modules operate. CORDIS-ANIMA models are networks of interconnected <MAT> and <LIA> modules.

GENESIS lets the user operate at the elementary level, since models are created by direct graphical manipulation of the modules on a virtual workbench. While these manipulations take place in the 2D space of the workbench, the simulation space is one-dimensional. The modules can only move in the direction that is perpendicular to the workbench; positions and velocities are computed along this axis. Consequently, the workbench space is only topological.

2.1.2. Relations with other physical modelling schemes

PM schemes have been extensively compared in [7], so we only give here an overview of some important points.

Waveguide techniques [15] and Modal synthesis [1] can be thought of as “high-level” PM schemes compared to mass-interaction PM. Indeed, both directly simulate complex phenomena (respectively wave propagation and vibration modes) that are also observable in mass-interaction PM, but without being described by the underlying formalism. With CORDIS-ANIMA, these phenomena *emerge* from simpler ones, i.e. the movements of interacting punctual masses.

The “atoms” of any CORDIS-ANIMA model have a direct physical meaning that is easily understood by people with no particular mathematical or physical background. GENESIS is commonly taught using references to real-world objects (e.g. balls and springs). The “atoms” of a waveguides model (i.e. delay lines and digital filters) or modal model (i.e. modal oscillators) may be more difficult to understand for a non-specialist, since they refer to more complex phenomena.

CORDIS-ANIMA is a modular system, which sometimes implies higher computing costs than other PM schemes (e.g. for 1D models). The trade between modularity (which brings generality and flexibility), and computational efficiency is a classical issue in computer science. We think that strong modularity is highly desirable in this context, both for teaching and artistic purposes. For example, no more than 3 <MAT> and 3 <LIA> modules are needed in GENESIS to produce a plausible sound of a bouncing marble. Thus, the complexity of a model is not necessarily linked to the relevance of the sound it produces (which, in this example, resides in the precise timing of the sound events rather than in the timbre). A large part of the development of GENESIS’ model library is devoted to the search for such minimal models, whose simplicity balances the extra cost of modularity and allows better usability.

GENESIS is not the only mass-interaction PM environment for music creation. Cymatic [12] or pmpd [11] use very similar techniques while providing different modelling possibilities. Cymatic’s basic building blocks are strings, plates and boxes. The user is not able to define its own nonlinear interactions. While these choices provide performance improvements, they restrict the generality of the environment. In pmpd, the elementary objects are masses, like in GENESIS. The only available type of interaction is the linear viscoelastic link. pmpd models run in real-time, but at the control rate. This makes them mainly suitable for the interactive physical control of real-time audio synthesis or processing. Direct sound synthesis capabilities are limited by the absence of nonlinear interactions to provide excitation to vibrating structures.

2.1.3. Overview of GENESIS modules

The set of GENESIS’ building blocks is composed of:

- Linear modules: punctual inertia (MAS), fixed point (SOL), elasticity (RES), friction (FRO), elasticity and friction combined (REF) and second-order damped oscillator (CEL).
- Nonlinear interactions: the BUT and the LNL, which are described in the next section.
- Output modules: the SOX and the SOF, which respectively record a position and a force signal.

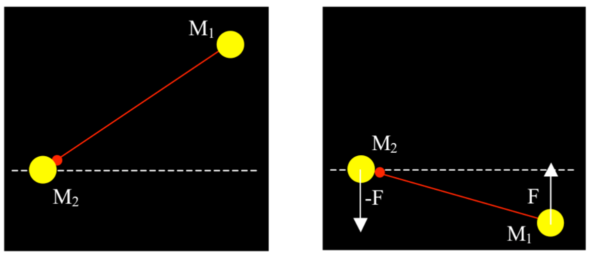
<MAT> modules (MAS, CEL, SOL, SOF) have an initial position; MAS and CEL modules also have an inertia parameter and an initial velocity. <LIA> modules have parameters that set their elasticity (K) and/or their friction coefficient (Z).

2.2. Nonlinear modules

Any physical modelling system for sound synthesis includes at least one nonlinear element, since nonlinearity is required to provide excitation to the simulated vibrating structure. GENESIS nonlinear elements are the following <LIA> modules.

2.2.1. The BUT module

The BUT module simulates a conditional viscoelastic interaction between two modules (Figure 1). When the difference between the positions of M_1 and M_2 is greater than a given threshold S, there is no interaction between them; when the difference is smaller than the threshold, the BUT simulates the effect of a zero-length damped spring between M_1 and M_2. The user can control the threshold and the parameters of the spring (stiffness and viscosity).



(a) (b)

Figure 1. Effect of the BUT module with a null threshold. (a) M_1 is above M_2: modules are free. (b) M_2 is below M_2: modules are linked.

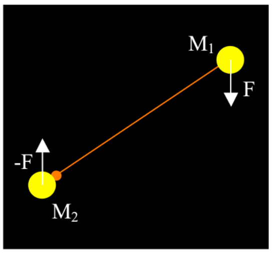
The BUT is an asymmetric module, since the value that is compared to the threshold is not the *distance* between the two modules, but the difference of their positions. The graphical representation of a BUT module includes a small dot indicating its orientation.

The most obvious application of the BUT module is the simulation of collisions between masses but it is used in a totally different way in the models we describe in Section 4.

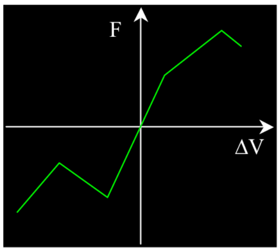
2.2.2. The LNL module

The LNL module is a user-defined nonlinear viscoelastic interaction. The user chooses the points defining two curves. The first one (called LNLK) gives the force to be applied to the modules according to the difference of their positions (nonlinear elasticity). The second curve (LNLZ) gives the force according to the difference of their velocities (nonlinear friction); see Figure 2. Elastic and friction forces are added and applied to the <MAT> modules linked by the LNL. According to the force curves, the LNL is symmetric or not. It may represent a pure elasticity or a pure friction.

Nonlinear interactions have many applications, ranging from the excitation of sounding structures (e.g. plucking and bowing) to the building of complex models with no real-world counterpart. As presented in Section 4, a novel use of the LNL module consists in setting temporary interactions between two objects.



(a)



(b)

Figure 2. The LNL module. (a) Graphical representation. (b) A velocity-force curve (LNLZ)

2.3. The GENESIS Instrumentarium

We are currently working on the development of a large library of GENESIS models that will cover most of the possibilities of the environment so far. This library, that we call the *Instrumentarium*, is not a mere collection of models. It will also include a detailed description of each selected model or category of models and will be integrated into a complete documentation of the conceptual and practical aspects of GENESIS. The first version of the Instrumentarium will be available with the next multiplatform release of the environment and, hopefully, will help learners build a deep knowledge of PM and GENESIS. It aims at meeting the same kind of needs as the *Csound Book* [2] do for learners of this other highly modular environment.

The study we present here was conducted with the aim of developing the Instrumentarium, thus it is important to detail the approach we adopted for this work.

Generally speaking, we do not try to *imitate* real-world instruments or phenomena, even though – as for any synthesis technique – this is a useful exercise for developing experience. We consider that the conceptual basis of CORDIS-ANIMA is sufficient to ensure that a large majority of GENESIS models will show physically plausible behaviour, thus producing correspondingly plausible sounds or sound structures. The rare cases where this statement may not be true are rigorously studied. Consequently, we build and study GENESIS models for themselves, while keeping real-world phenomena (such as strings nonlinearity, see Section 3) as references in the modelling process.

The building of the Instrumentarium consists of a large number of precise studies like the one we present here. Each study involves several steps. First, the direction to be explored is defined according to various goals. Then begins a phase during which a number of models are "empirically" built and evaluated against the initial objectives. An important guideline is the search for minimal models that exhibit interesting properties. Indeed, minimal models constitute a far better teaching support than complex ones; they are easier to understand and more usable. The last step is the precise analysis of the selected models. It aims at providing rules that will help users employ models in real situations. When possible, these rules are implemented in Excel-like calc sheets in order to provide fast calculation of common formulas.

3. NONLINEARITY AND SOUNDS

As any study of instrumental acoustics shows, the role of nonlinearity is essential in real instruments. First, the interaction between the exciter and the vibrating structure of an instrument is necessarily nonlinear, since this is the only way to produce high frequency movements (acoustical oscillations) from low frequency ones (gesture). Furthermore, nonlinear effects are present in the physics of *every* instrument family, and play an important role in the sound production mechanisms [9]. They are at the origin of many subtle phenomena that make the richness of natural sounds.

Particular nonlinear interactions have already been studied at ACROE and ICA laboratory, for example to simulate string bowing [10] or to improve the sound quality of 1D strings [5]. The models presented here are the result of a systematic exploration of the possible usages of GENESIS' nonlinear interactions with the aim of building models that behave *as if* their parameters or structure were evolving during the simulation.[1] The simulation of parametric changes led to models similar to those presented in [5], with the extra possibility to perform timbre morphing by accentuating nonlinearity. We only present here the results concerning structural changes.

[1] In GENESIS, parameters and connections between modules (i.e. structure) are chosen at design time and remain the same during the simulation. The main reason for this is that dynamic parametric or structural changes may destroy the energetic consistency of a model and lead to instability.

4. MODELS WITH TIME-CHANGING STRUCTURE

4.1. Relation with real-world instruments

Real-world instruments generally have a fixed physical structure. Modifications performed upon an instrument while playing it mainly involve changing the size or tension of vibrating structure (string instruments, percussions) or of resonators (wind instruments). Meanwhile, the intrinsic properties of the different components remain the same, the main reasons for this being that (1) matter is not transformable at will; (2) instrumentalists are generally reluctant to perform experimental actions (such as breaking and sticking) on their instruments, which is perfectly understandable.

Virtual instruments built with PM are not submitted to these constraints. A method for instrument morphing has been proposed [13]. It allows continuously morphing resonators (for example, from a guitar body to a violin body). The method that we propose here allows transforming a model whatever the role it plays in the sound production chain. It is particularly interesting when applied to "compositional models".

4.2. Temporary viscoelastic interactions

This section describes the so-called virtual sticking devices that are used to dynamically modify the structure of a GENESIS model. The basic idea is to set temporary viscoelastic interactions between MAS modules belonging to different structures (thus resulting in a third new object Figure 3), or to a single object (thus resulting in an evolution of its vibrating properties).

The temporary links may be as stiff as stability considerations allow, which is generally sufficient to "stick" masses together. We will consider here that two <MAT> modules are stuck if the amplitude of their relative movements is negligible compared to the amplitude of their common movements.

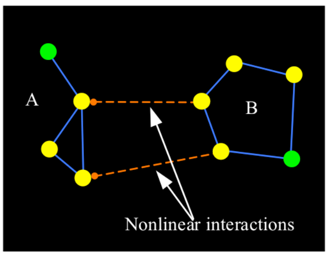


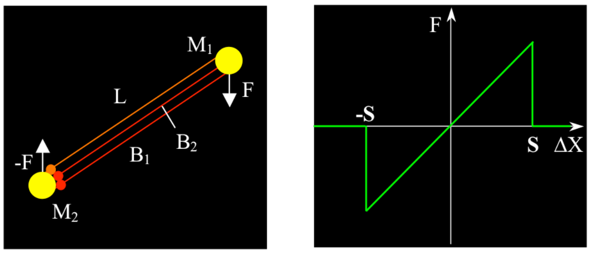
Figure 3. A temporary link between two simple structures. Structures A and B are "stuck" together with nonlinear interactions.

4.2.1. A simple sticking device

The basis of the temporary interaction is a combination of an elastic LNL module, L, and two viscous BUT modules, B_1 and B_2 (Figure 4-a) between two <MAT> modules M_1 and M_2 - which are supposed to be of the same inertia, m. The LNLK curve of L is shown in Figure 4-b. It is a symmetric elastic interaction with a threshold S. Thus, M_1 and M_2 are linked by a zero-length spring when their distance is smaller than S. The first BUT module (B_1) has the same threshold S, and its viscosity Z_1 is chosen according to the stiffness of L (K_L) so as to damp the relative oscillations between M_1 and M_2 when they are linked – this is the equivalent of *critically damping* for a second order mechanical oscillator. We have:

$$Z_1 = 2\sqrt{K_L m} - K_L \qquad (1)$$

The second BUT module is used to cancel the effect of B_1 when M_1 is below M_2 and their distance is greater than S (Figure 5); its threshold is -S and its viscosity -Z_1. This allows for the whole interaction (B_1+B_2+L) to be symmetric.



(a) (b)

Figure 4. The simple sticking device. (a) Representation of the <LIA> modules. (b) The LNLK curve of module L.

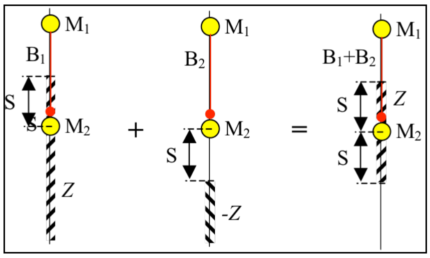


Figure 5. The combined effect of B_1 and B_2

The combined effect of these three modules is the following. When the distance between M_1 and M_2 is smaller than S, the MAT modules are attracted one by the other. They tend to occupy the same position, without oscillating. They are temporarily "stuck" together. Obviously, this sticking is not perfect. It is easily broken if other forces cause the distance to be greater than S. Another issue of this method is that M_1 and M_2 cannot be at the same position *without* being in interaction. This constraint reduces the generality of the sticking device. Moreover, it would be useful to set *any* possible interaction between M_1 and M_2, while we are so far limited to a critically damped viscoelasticity.

4.2.2. A general sticking device

In order to get a more general method of temporarily linking masses, we built a more complex sticking device (Figure 6). The device is composed of two "intermediary" MAS modules, M_{C1} and M_{C2}, with the same inertia m_C. These modules are respectively linked to M_1 and M_2 with identical simple sticking devices (L_{S1}

and L_{S2}) and linked together by a certain interaction R. R is the interaction we want to set between M_1 and M_2.

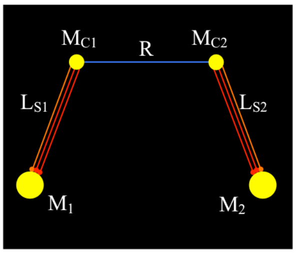
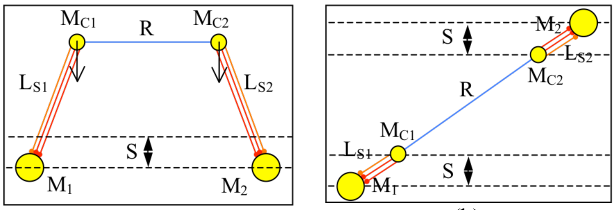


Figure 6. The general sticking device applied to MAS modules M_1 and M_2.

First, M_{C1} and M_{C2} are at the same position, at a distance from M_1 and M_2 greater than S (Figure 7-a). They are moving towards M_1 and M_2, which are first supposed to be at rest. When they cross the threshold, they are attracted by M_1 and M_2 and quickly stabilize at the same position. If the interaction between M_i and M_{Ci} is very stiff[2], M_{Ci} closely follows M_i. Thus, as a first approximation, each M_i-M_{Ci} pair may be considered as a single MAS module with an inertia equal to the sum of the inertias of M_i and M_{Ci}, as long as the temporary interaction is not broken. Consequently, we can state that a temporary interaction R is established between M_1 and M_2, at the expense of a mass increase. M_{C1} and M_{C2} inertia may be relatively small (about a tenth of m) so as to reduce the amount of inertia added to the system.



(a) (b)

Figure 7. Two situations with the general sticking device: (a) before sticking; (b) just before breaking. The threshold is accentuated in both figures.

The temporary link "breaks" if the distance between M_1 and M_2 becomes greater than a certain threshold S_B that is easily calculated:

$$S_B = S\frac{K_L + 2K_R}{K_R} \tag{2}$$

where K_L is the stiffness of the central portion of L_{S1} and L_{S2}. We see that S_B is at least two times greater than S.

There is an interesting way to break the temporary link at a chosen time. It consists in striking M_{C1} and M_{C2} with a very high velocity MAS, so that they get out of the threshold in only *one* simulation step (Figure 8). In this case, the interaction is interrupted immediately and the sudden movement of M_{C1} and M_{C2} does not influence M_1 and M_2. Thanks to time quantization, it is possible to break objects without making any noise!

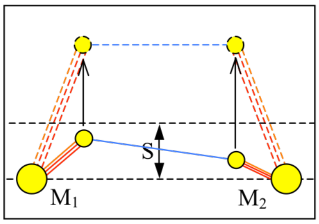


Figure 8. Breaking a temporary interaction without making noise. M_{C1} and M_{C2} get out of the threshold in one simulation step.

The main properties of the general sticking device are:

- The interaction created by the device is at least twice as strong as that of the simple sticking device ($S_B > 2S$).
- The device allows setting any interaction between M_1 and M_2, provided that its stiffness is not greater than m_C, for stability's sake.
- The position of M_1 and M_2 are not constrained, in particular they can be at the same position without being linked.
- It is possible to break the interaction without exciting the structures that were linked.

The general sticking device has two main drawbacks. First, when the link is established, the intermediary masses gain energy, since, from then on, they are attached to an elongated spring! This energy is transmitted to M_1 and M_2 and to the structures they belong to. Decreasing S reduces this unwanted excitation, but this also results in a weaker link. Secondly, the sticking device adds damping to the model, resulting in shorter decay time of higher partials. However, these side effects are unavoidable as long as we work with fixed parameters modules, i.e. as long as we keep physical consistency.

4.3. Applications

4.3.1. The (St)ring

This model demonstrates one of the possibilities of the general sticking device. It is composed of three strings (S1, S2 and S3); S1 is the only one being attached to a SOL module (Figure 9).

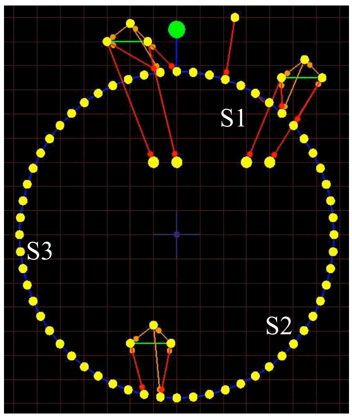


Figure 9. A three-segment (St)ring

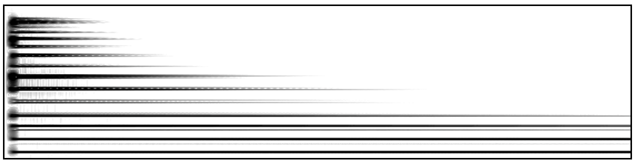
[2] In the GENESIS unit system, which is different from the real-world unit system, this corresponds to the numerical values of K_L and m_C being of the same order of magnitude

S1 is struck at the beginning of the simulation. Then, one after the other, three sticking devices connect S1 to S2, S2 to S3 and finally S3 to S1. Thus, this model is an open string that progressively gets longer, then turns into a ring.

Each time a segment is added to the previous one, the number of modes increases by the number of MAS modules that are added[3] and the fundamental frequency decreases since the vibrating structure gets longer (Figure 10-a**).** When S3 connects to S1, the topology of the object changes; this evolution is clearly perceptible in the sound produced by the model, since timbre, which is pseudo-harmonic before the connection, becomes totally inharmonic (see the last part of the spectrogram in Figure 10-a).

(a)

(b)



(c)

Figure 10. Spectrograms of the first 4 seconds of sounds produced by: (a) the (St)ring; (b) the (St)ring with all interactions set; (c) an equivalent linear ring. Linear frequency scale, max. frequency: 2200 Hz.

In order to evaluate the effects of the sticking devices, we compared the sound produced by the (St)ring with all connections established (Figure 10-b) to the sound of a an equivalent linear ring (Figure 10-c).[4] While the frequency of partials is nearly identical in both sounds, their decay time is much shorter in the nonlinear model. After 4 seconds, only two partials are still audible in the first sound, while there are five in the second sound. This clearly shows that critical damping plays an important role in vibrating properties of the whole model and that M_i-M_{Ci} pairs are not equivalent to a single MAS module.

Both sounds are identified as being produced by metallic objects, but the second one may be perceived as being unnaturally sustained. Although the over-damping introduced by the sticking device may not always be desirable, it doesn't seem to affect sound plausibility.

[3] The number of vibrating modes of a linear GENESIS model is equal to the number of its degrees of freedom, i.e. the number of its MAS modules. [13]

[4] In the linear model, each M_i-M_{Ci} pair was replaced by a single MAS module with inertia equal to m+m_C

Due to the discrete nature of CORDIS-ANIMA models, this method of structural evolution is not very well adapted to the production of continuous frequency and timbre changes. Its interest is rather in the articulation between micro- and macrostructure. In this example, the model is just struck once at the beginning of the simulation. But, as any sounding model, it could be "played" by another complex model, such as one of those presented by Cadoz [4]. In this case, the evolution of the structure could be correlated by several means to the actions of the "player". This is illustrated in a simple manner by the (St)ring. Indeed, the sticking devices used in this model are not "sent" towards the string segments using initial velocity. Instead, the oscillations of the segments progressively accelerate them via a unidirectional friction, until the connection is established. Consequently, the user does not choose the precise moment of each connection. The higher the amplitude of the oscillations, the sooner it happens. This may be a rather dumb example, but it suggests new ways of thinking the relationships between the micro- and the macrostructure of music generated by mass-interaction PM.

4.3.2. The reconfigurable strings

The "reconfigurable strings" model is made of two groups of three differently tuned open strings. The free endpoint of each string is linked to all the free endpoints of the other group's strings with simple sticking devices (Figure 11). When two endpoints come close one to the other, they are temporarily linked, thus creating a new string fixed at both ends. The entire right group has a slow sinusoidal movement caused by a very heavy oscillator that carries the "bridges". As a consequence, the connections between strings keep setting up and breaking during the simulation.

These structural evolutions produce timbre and pitch changes, just like what happens in the (St)ring. The strings can be precisely tuned in order to choose the timbre and pitch classes produced by the model – obviously, other strings could be added in order to have richer possibilities. For example, it can be interesting to have a similar string in each group so that harmonic sounds are produced when both are connected.

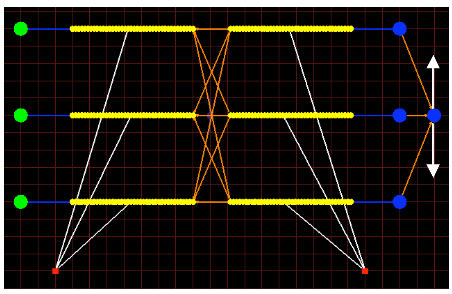


Figure 11. The reconfigurable strings. The right part of the model (the three strings and their bridges) is moved up and down by the oscillation of the module surrounded by arrows.

Strings are excited when a connection is set or broken, so this model produces complex and partially unpredictable sequences of sounds (Figure 12), because the generation of events depends on the very complex movements of strings' endpoints. However, since the right group has a regular global movement, these sequences exhibit pseudo-periodicity.

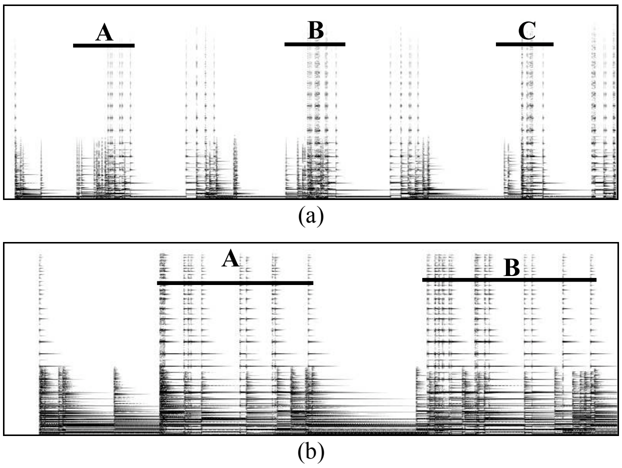


Figure 12. Spectrograms of the first 24 seconds of sound produced by two versions of the reconfigurable strings. Linear frequency scale, max. frequency: 5000 Hz. (a) 8 s period, high damping. (b) 11 s period, medium damping.

In the model that generated the first sound (Figure 12-a), the global movement of the right strings had a period of 8 seconds. The results of this regular oscillation can be seen in the spectrogram. It shows groups of sound events happening approximately every 4 seconds (the half-period), with a strong similarity between groups separated by 8 seconds (e.g. A, B and C). The second sound (Figure 12-b) was produced by a slightly different version of the model (its period was of 11 seconds and the oscillations of the right part had a smaller amplitude). Two sound groups having a very similar structure are clearly visible in the spectrogram. In both cases, events groups do not have exactly the same duration or the same structure (for example, group C of the first sound is shorter than groups A and B).

One can say that the relationship between regularity and irregularity is one of the bases of musical composition. The reconfigurable strings generate sound sequences where rhythm and chaos are both present and can be "mixed in the right proportions". This is done by carefully choosing (1) the distance between the strings, (2) the threshold of the sticking device and (3) the amplitude of the heavy oscillator. For example, when the strings are far from each other compared to the sticking threshold, there are few interactions between them and the rhythm imposed by the oscillator clearly appears. When they are close to each other, the sound sequences produced by the model tend to be more complex. The amplitude of the right part of the model determines the duration of rest sections in the sound. When the amplitude is high, the right strings periodically get above or below the left strings, which results in a halt in sound events generation.

Tuning the reconfigurable strings involves finding the right balance between those parameters, which sometimes may be difficult due to the pseudo-chaotic nature of this model. In order to explore the large set of possible sound sequences, the musician is then invited to adopt an experimental approach that will led him or her to an empirical knowledge of the model's behaviour. However, this exploration can be guided by the general rules that we have stated in the previous paragraph.

In this model, the relationship between, micro- and macrostructure is more "intimate" than in the (St)ring, because event generation and sound production are performed by the same structure.[5] The reconfigurable strings model is a kind of musical automata; it generates surprising, partially controllable and, we think, musically relevant sound sequences.

5. DISCUSSION

GENESIS compositional models that had been presented so far were composed of several static components, at least a virtual player and its virtual instrument, linked by nonlinear interaction that basically transmit energy between them. The method that we introduced in this article enables transforming these structures during the simulation. This allows more complex and potentially more expressive relations between the micro- and the macrostructure of the music generated. The movements of the low-frequency components of the models (e.g. the heavy oscillator of the reconfigurable strings) may modify the properties, not to say the *nature*, of the high-frequency components. This is a new possibility in physical modelling.

The models we presented are rather simple, but they demonstrate the potential of this method, and suggest several applications (such as dynamically carving or weighing down vibrating structures). We will continue investigating these applications in order to add them to the Instrumentarium. We will particularly study the properties of the operation consisting in turning any linear model into a nonlinear one with time-changing structure.

6. ACKNOWLEDGMENTS

This work has been supported by the French Ministry for Culture and Communication and the French Ministry for Higher Education and Research.

7. REFERENCES

[1] Adrien, J.M. "The Missing Link: Modal Synthesis", in *Representation of Musical Signal*, G. De Poli, A. Picialli, and C. Roads, eds, MIT Press, Cambridge, Massachusetts, 1991.

[2] Boulanger, R. *The CSound Book*, MIT Press, Cambridge, Massachusetts, 1999.

[5] It is impossible here to separate the exciter from the vibrating structure, as can be done for "classical" GENESIS models.

[3] Cadoz, C., Luciani A., Florens, J.L. "CORDIS-ANIMA: A Modeling and Simulation System for Sound and Image Synthesis – The General Formalism", *Computer Music Journal* 17(1), 1993.

[4] Cadoz, C. "The Physical Model as Metaphor for Musical Creation “pico..TERA”, a piece entirely generated by physical model", *Proceedings of the 2002 International Computer Music Conference,* Göteborg, Sweden, 2002.

[5] Castagné, N., Cadoz, C. "Physical Modeling Synthesis: Balance Between Realisme and Computing Speed", *Proceedings of the DAFX-00 Conference*, Verona, Italy, 2000.

[6] Castagné, N., Cadoz, C. "GENESIS: A Friendly Musician-Oriented Environment for Mass-Interaction Physical Modeling", *Proceedings of the 2002 International Computer Music Conference*, Göteborg, Sweden, 2002.

[7] Castagné, N., Cadoz, C. "10 Criteria for Evaluating Physical Modelling Schemes for Music Creation" *Proceedings of the DAFX-03 Conference*, London, UK, 2003.

[8] Chafe, C. "Case Studies of Physical Models in Music Composition", *Proceedings of the 18th International Congress on Acoustics*, Kyoto, Japan, 2004.

[9] Fletcher, N. H. "The nonlinear physics of musical instruments", *Reports on Progress in Physics* 62 (723-764), 1999.

[10] Florens, J.L. "Expressive Bowing on a Virtual String Instrument", *Proceedings of the 5th International Gesture Workshop*, Genova, Italy, 2003.

[11] Henry, C. "Physical Modeling for Pure Data (pmpd) and real time interaction with an audio synthesis", *Proceedings of the Sound and Music Computing Conference SMC04*, Paris, France, 2004.

[12] Howard, D. M., Rimell, S., Hunt, A. D. "Force Feedback Gesture Controlled Physical Modelling Synthesis", *Proceedings of the NIME-03 Conference*, Montreal, Canada, 2003.

[13] Incerti, E. "Synthèse de Sons par Modélisation Physique de Structures Vibrantes", PhD Thesis, INPG, Grenoble, France, 1996.

[14] Penttinen, H., Karjalainen M., Härmä, A. "Morphing Instrument Body Models", *Proceedings of the DAFX-01 Conference*, Limerick, Ireland, 2001.

[15] Smith, J. O. "Physical Modeling Using Digital Waveguides", *Computer Music Journal* 16(4), 1992.